Total-Ionizing Dose Mechanisms in Antimony based CMOS Transistors with High-k Dielectric

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Abstract: *In this paper we present the effect of ionizing radiation on n and p-channel Antimonide based (Sb) based Quantum Well-Metal-Oxide-Semiconductor-Field-Effect Transistor (QW-MOSFETs). QW-MOSFET's were fabricated on n-channel InAsSb QW and p-channel InGaSb QW and then exposed to ionizing radiation. The n-channel InAsSb QW shows higher radiation sensitivity than the p-channel InGaSb QW due to enhanced hole trapping occurring at the AlInSb barrier/InAsSb QW interface. The transient response of the InAsSb QW MOS structure to radiation induced electron-hole pair generation was evaluated using TCAD simulation.*

Introduction

There is tremendous interest in Antimonide based (Sb) compound semiconductors due to their superior electron and hole transport properties. InGaSb and InAsSb quantum wells (QWs) (Fig.1) are of particular interest as InGaSb offers hole mobilities over 10X than that seen in Si, while n-channel InAsSb QWs offer electron mobilities over 60X over Si (Fig.2). Further, InAsSb and InGaSb QWs share a common $Al_{0.8}Ga_{0.2}Sb$ buffer (Fig.1), facilitating the integration of both p and n-channel devices on a common III-V platform. These strengths make Sb-based devices applicable for use in low power high-speed digital and millimeter wave applications. Sb device technology needs to be resilient to ionizing radiation. To date, the study of the impact of ionizing radiation on III-V devices has been limited to GaAs metal semiconductor field effect transistors (MESFET's), InGaAs/ InAlAs HEMTs, and InAs/AlSb HEMTs [1-2] In this work, we study and analyze the effect of ionizing radiation on Sb-channel n- and p-channel QW MOSFETs.

Antimony Based Transistors

The InAsSb n-channel and InGaSb p-channel QW-MOSFETs used in this work were grown on separate substrates. The InAsSb n-channel hetrostructure was grown on a GaAs substrate with a metamorphic $Al_{0.8}Ga_{0.2}Sb$ buffer (Fig 3). The QW is undoped while the $Al_{0.8}In_{0.2}Sb$ barrier layer has been delta-doped with Te to provide carriers to the access regions. A hybrid GaSb/InAlSb barrier layer is utilized. Sb-based materials are especially reactive in atmosphere resulting in a poor high-κ

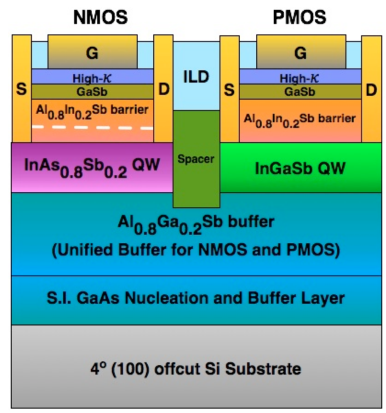

Figure 1. InAlSb and InGaSb QW heterostructures on AlGaSb common metamorphic buffer

dielectric/antimonide interface. Adding a thin layer of GaSb to the barrier has been shown to improve passivation of the semiconductor/dielectric interface. The InAsSb QW-MOSEFTs were fabricated using a gate-last process with a Al_2O_3/HfO_2/high-κ gate dielectric deposited via Atomic Layer Deposition (ALD) [3-4].

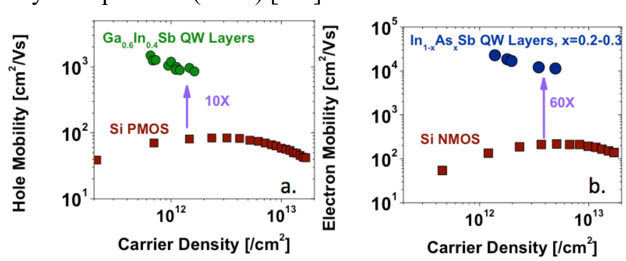

Figure 2. (a) Hole mobility versus hole sheet density at T=300K for Si, and GaInSb QW (b) Electron mobility versus electron sheet density at T=300K for Si, and InAsSb, measured using Hall transport measurements. [3,5]

The InGaSb p-channel heterostructure was grown on a GaAs substrate using the same metamorphic $Al_{0.8}Ga_{0.2}Sb$ buffer as the n-channel device (Fig 3). A GaSb/AlInSb hybrid barrier is utilized to confine the InGaSb channel. A thin layer of GaSb is again used to improve the dielectric/semiconductor interface. The p-channel InGaSb QW MOSFETs were fabricated using a self-aligned gate-first process [5,6] with ALD Al_2O_3/high-κ gate dielectric. The high quantization in the resulting $AlInSb/GaSb/Al_2O_3$

QW lowers lowering the available charge near the interface, thereby reducing the detrimental effect of interface states on hole mobility. [7]

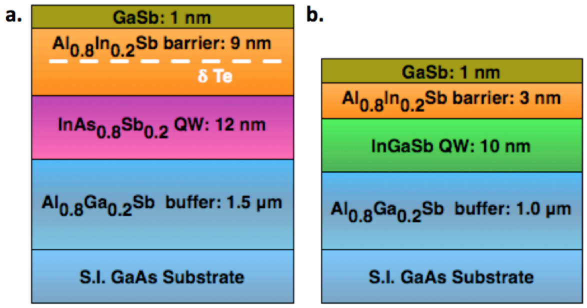

Figure 3. (a) InAlSb and (b) InGaSb QW heterostructures

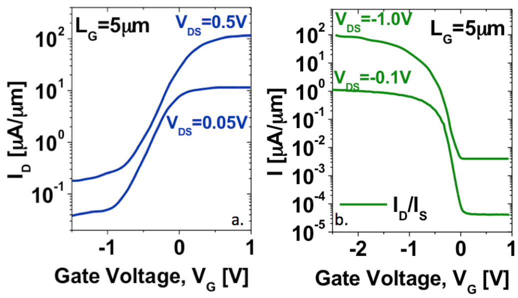

Figure 4. (a) I_D-V_G characteristics for L_G=5um InAsSb QW-MOSFET at T=300K [3] (b) I_D-V_G characteristics for L_G=5um InGaSb QW-MOSFET at T=300K [5]

The I_D-V_G response for long channel (L_G=5.0 um) InAsSb n-channel and InGaSb p-channel QW-MOSFETs are shown in Fig.4 Effective mobilites were extracted from both structures using the split-CV method [3,5] (Fig.6). The InAsSb n-channel device has a peak effective electron mobility over 5,970 cm^2/V-s, while the InGaSb p-channel shows peak hole mobility of over 900 cm^2/V-s. RF characterization of short channel InAsSb QW-MOSFET's show a cutoff frequency of 120 GHz and an effective source injection velocity 4X higher than Si NMOS and 1.5X higher than InGaSb NMOS.

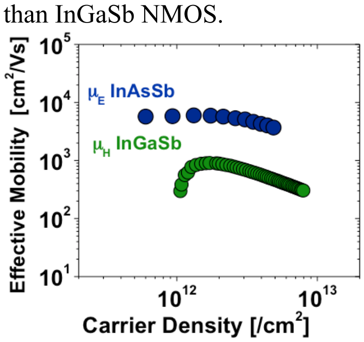

Figure 5. Extracted effective mobility for InAsSb and InGaSb QW's as a function of carrier density [3-5]

Total Ionizing Dose

Total Ionizing Dose (TID) experiments were performed on the InAsSb and InGaSb QWMOSFET's. These devices were subjected to X-ray radiation from a 10 keV, source with a dose rate 31.5 krad SiO_2/min As shown in Figs 6-8 the InAsSb when exposed to ionizing radiation at high vertical electric field (V_G=1.0V) showed significant negative threshold voltage V_T shift. At lower vertical electric field (V_G=0.2V) the threshold voltage shift was less. Twenty-four hours after radiation exposure the device threshold voltage completely recovered. For InAsSb QW-MOSFET, the sub-threshold slope (SS) and transconductance remained relatively unchanged with dose at low vertical electric field, while this was not the case at high vertical electric field (Fig. 9). The negative V_T shifts are indicative of induced positively charged hole trapping due to ionizing radiation.

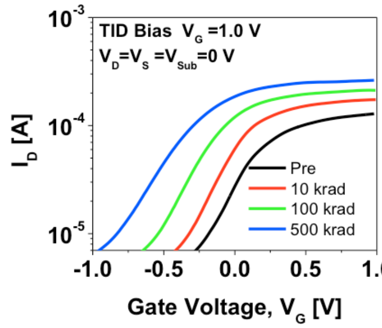

Figure 6. Radiation induced V_T shift in InAsSb n-channel QW-MOSFET I_D-V_G characteristics

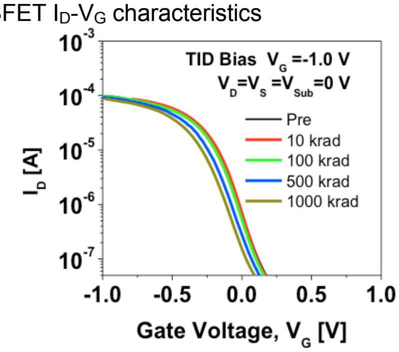

Figure 7. Radiation induced V_T shift in InGaSb p-channel QW-MOSFET I_D-V_G characteristics

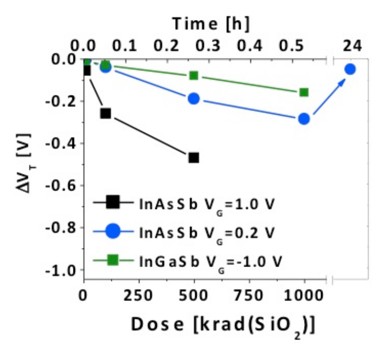

Figure 8. Radiation induced V_T shift as a function of dose for n-channel InAsSb and p-channel InGaSb QW-MOSFETs

The InGaSb p-channel devices showed sensitivity to ionizing radiation. As shown in Figs. 8-9 there was a negative threshold voltage shift at high vertical electric field (V_G=-1V). For the p-channel InGaSb there is a slight degradation in SS and transconductance with increasing radiation dose (Fig.10). However, as shown in Fig. 8, the V_T shifts associated with increasing ionizing radiation dose are much less for the p-channel InGaSb device compared to the n-channel InAsSb device.

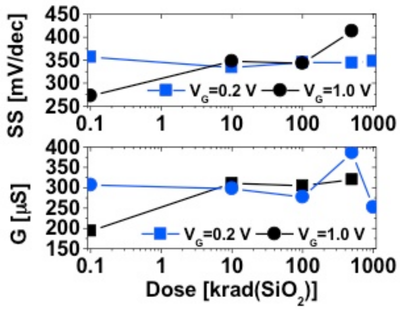

Figure 9. Sub-threshold swing (SS) and transconductance as a function of radiation dose for n-channel InAsSb QW-MOSFET

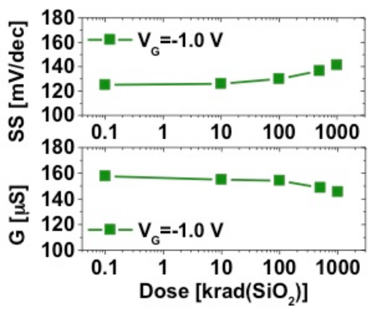

Figure 10. Sub-threshold swing (SS) and transconductance as a function of radiation dose for p-channel InGaSb QW-MOSFETs

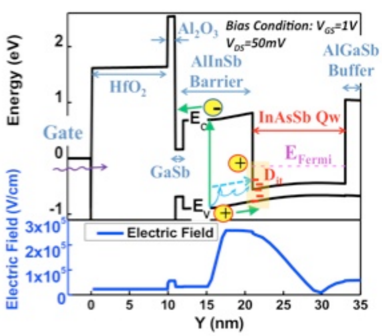

Figure 11. Energy Band Diagram InAsSb n-channel QW-MOSFET

For the n-channel InAsSb NMOS device the source of these trapped charges could be from the high-κ /semiconductor interface or the AlInSb barrier/InAsSb QW interface. The sensitivity to vertical electric field is an indication that the hole trapping mechanism is related to the AlInSb barrier/InAsSb QW interface and not the high-κ interface. As shown in Fig. 11 at V_G=1.0V (on-state) the electric field reaches its maximum in the depleted AlInSb barrier. The vertical field assists the (e/h) pair generation in the barrier. The direction of electric field is towards the quantum well interface, which causes holes drifting to the

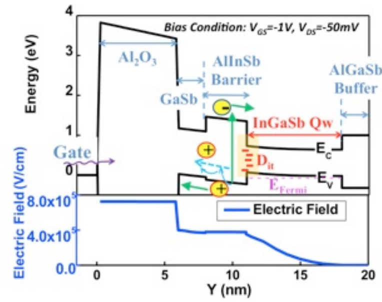

Figure 12. Energy Band Diagram for InGaSb p-channel QW-MOSFET

traps at the interface. For the InGaSb PMOS device, the high field remains in the high-k and the barrier at V_G=-1V (on-state). The vertical field pulls the holes away from the InGaSb quantum-well and the trapping takes places at the high-κ/GaSb interface (Fig.12). This results in lower threshold voltage shift. Further, as the holes are trapped away from the QW, we observe less impact on the sub-threshold and the transconductance in case of p-channel devices. Thus, the effect of ionizing radiation is less for the p-channel device than the n-channel device.

Transient Response

To identify the relevant physics of radiation induced transient response and carrier transport in the Sb quantum well MOSFETs, we set up a numerical device simulation using Sentaurus TCAD [8] for depletion-model InAsSb n-MOSFET. The simulation self-consistently solved the 1-D Schrodinger equation to calculate the sub-bands due to quantization with a field dependent mobility model incorporating velocity overshoot due to non-local transport Fig. 13 (a) shows the simulated device structure with a QW thickness of 12 nm and L_G of 150 nm. I_{DS}-V_{DS} characteristics and the quantum well sub-bands for device under zero bias condition are shown in Fig. 13 (b-c). To investigate the effect of the radiation, we assumed charge deposition along the normally injected radiation track in InAsSb quantum-well region. The Heavy Ion Model in TCAD Sentaurus was utilized, with charge deposition induced at t=20 ps. The radiation induced electron-hole pairs follow a Gaussian distribution with constant linear energy transfer (LET) along the track and a spatial dispersion width, W_t=10 nm. The generated charge results in a transient current under device off-state (V_{GS}=-2V, V_{DS}=0.5V) condition (Fig 14). Fig. 14 shows the transient current normalized to the on-current at V_{DD}=0.3, 0.4 and 0.5 V at LET = 50 fC/µm and 100 fC/µm, respectively. The magnitude and duration of the normalized transient current both increase with V_{DD} which also strongly impact the device off-state at higher LET due to the hole storage in the quantum-well region.

Hole storage induced bipolar gain effect strongly impact the radiation induced transient current profile in fully-depleted n-channel devices (e.g. Si, III-V FinFET) [9]

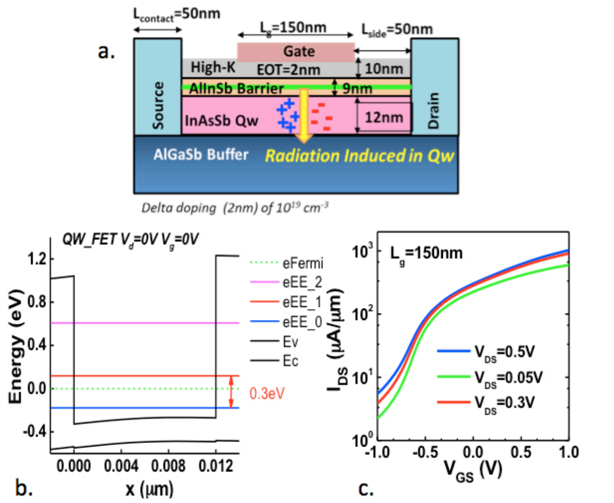

Figure 13. (a) Device schematic of 12 nm thick InAsSb quantum well n-MOSFET with AlInSb barrier used in simulation. Radiation strike is induced in the mid-channel of the quantum-well. (b) Band diagram and sub-bands for the InAsSb quantum-well at V_{DS}=0V, V_{GS}=0V. (c) Simulated $I_{G=DS}$-V_{GS} for the n-channel InAsSb depletion mode QW-MOSFET.

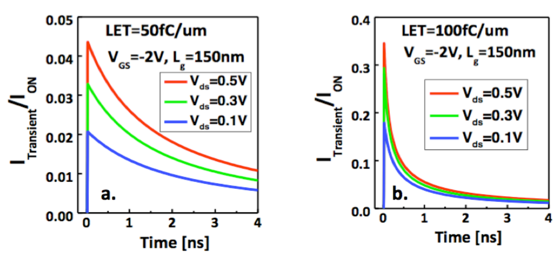

Figure 14. Soft error transient response in n-channel InAsSb QW- MOSFET for (a) LET= 50fC/μm and (b) LET= 100fC/um

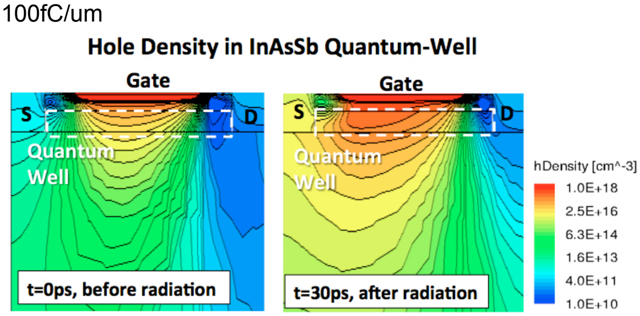

Figure 15. Hole density at InAsSb quantum-well before (t=0ps) and after (t=30ps) radiation at LET=100fC/μm, V_{DS}=0.5V, V_{GS}=-2V. Hole-storage induces the bipolar gain effect which increases the transient current magnitude and duration.

Fig. 15 shows the hole density before (t=0 ps) and after (t=30 ps) radiation in InAsSb quantum well n-MOSFET. The stored holes lower the source barrier and cause additional carriers injected in the channel of the InAsSb MOSFET to recombine, which causes the increase of the total collected charge and the magnitude and duration of the transient current.

Conclusion

Effect of ionizing radiation on Sb-based n- and p-channel QW MOSFETs has been studied for the first time. The n-channel InAsSb QW exhibits a higher radiation sensitivity than the p-channel InGaSb QW. For the NMOS device the there is hole trapping occurring at the AlInSb barrier/InAsSb QW interface. In ON state the vertical field is assisting with (e/h) pair generation in the barrier. The direction of electric field towards the quantum well interface results in holes drifting to the traps at the interface. For the InGaSb PMOS device, the high field remains in the high-κ and the barrier when the device is in the ON state. The vertical field pulls the holes away from the InGaSb quantum-well with trapping occurring at the high-κ GaSb interface. This results in lower threshold voltage shift for the p-channel device.

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